Metal Matrix Composite Brakes Using Titanium Diboride

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National Laboratory Impact Initiative

Energy Materials Network

Project ID mat142

Overview

Timeline

- Project Start Date: Sept 2017
- Project End Date: Sept 2020
  - 75% Complete

Budget

- Total project funding
  - DOE - $300k
  - Arconic $360.8k (in-kind)
- 45/55 Cost Share with Arconic
- Funding Received: FY17 $300k

Barriers

- Barriers to more widespread use of MMCs for vehicle lightweighting are*:
  - the costs of the feedstock, especially the insoluble reinforcement (particle, whisker, or fiber)
  - the cost of combining the reinforcement with the matrix in production
  - the cost of shaping / machining MMC components.

Partners

- LightMat CRADA Partner: ARCONIC
- Lab Lead: Pacific Northwest NATIONAL LABORATORY

*USDRIVE Materials Technical Team Roadmap, October 2017, section 5.7

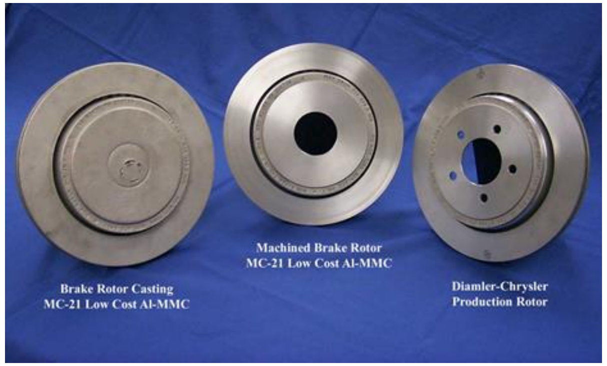
Relevance

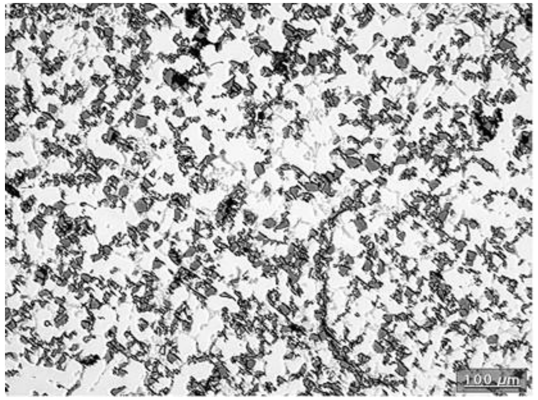
Objective

- Reduce the weight of brake rotors by >50% over the current cast iron materials
- Improve brake performance, wear life, and life cycle cost over cast iron systems
- Develop an Aluminum MMC material that shows appropriate wear resistance and tribologic properties
- Show the potential for a cost / benefit ratio appropriate for commercial development

Impact

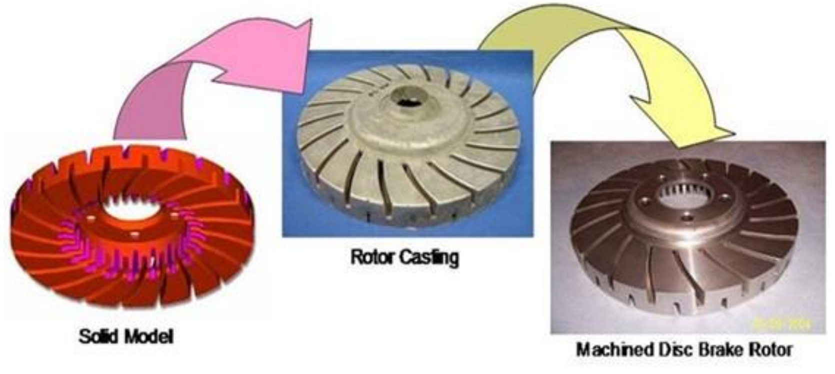
- A 50% weight saving in the rotor has been calculated to correspond to an improvement in fuel economy of 0.25 mpg due to weight reduction and lower rotational inertial energy losses (This number can be much higher in vocational vehicles)
- Aluminum MMC rotors may show significant life cycle cost saving and environmental benefit from reduced wear rate





Relevance

Drivers for Change in Braking Systems



- Aluminum MMCs can provide combinations of high friction coefficient, particular heat transfer characteristics and increased wear life that can **favorably affect system life cycle cost.**
- A 50% increase in wear life can **double the interval between rotor change-outs** and can affect the economics for those vehicle sensitive to down time
- A 50% savings in mass in a rotating and unsprung location can lead to a **0.25 mpg fuel saving** in a mid-sized car, potentially higher in high duty cycle –buses or city driving
- **Environmental Concerns-** “Wear particles from cast iron brakes are the second largest source of particulate emissions from a vehicle. In urban areas, around 55% of total non-exhaust PM10 (particulate matter smaller than 10 micrometers) emissions is from brake wear.” *

* https://thebrakereport.com/is-now-the-time-for-lightweight-brakes/

Relevance

Why change now?

The landscape has changed in the last 10 years

- Energy harvesting in electric/hybrid vehicle operation decreases the amount of energy that must be dissipated by the mechanical brakes by as much as 40%
    - Energy harvesting can allow for much lower front brake temperatures, enabling the use of lighter weight, lower melting temperature alloys as rotors
- Cast Iron rusts and rusty surfaces are hard to manage in brake-by-wire systems that are tasked with balancing mechanical brake force with energy harvesting
    - Consumers demand a smooth stop (Driver feel and NVH issue).
    - Corrosion resistant and low wear alloys (aluminum MMCs) may provide better control.
- The next generation of vehicle may need drastically improved durability and longer maintenance intervals if they are to be used in new mobility strategies (ride share, fleet ownership, etc.)
    - **TiB_2 reinforcement** offers an opportunity to improve wear resistance at a lower particle loading because of improved ceramic – aluminum bonding
- SiC reinforcement is costly when prepared for inclusion in an aluminum composite (Particle size fraction constraints, SiO_2 coating, etc.). **TiB_2 has much improved wetting** with aluminum allowing for finer particle size, better homogeneity and may prove to be lower cost overall due to lower particle loading required and reduced compositing time for the same friction and wear performance.

Approach

Cast TiB_2 reinforced aluminum brake rotors in several different reinforcement loadings and test for friction and wear performance

Task 1 - Raw Material Production

Arconic Technology Center (ATC) will produce 70kg-50 volume percent Al-TiB2 master alloy and 150kg A356 casting alloy to PNNL.

Task 2 - Casting of MMC Plate

PNNL will use the Al-TiB2 master alloy along with the A356 aluminum to cast 4 MMC billets of MMC composition (5, 10, 15, 20 vol% TiB2) utilizing PNNL MMC casting technology. Effort will develop high speed compositing techniques to mix TiB2 particulate into the aluminum matrix to address cost barriers associated multistep Al-SiC MMC casting processes in current practice

Task 3 - Machining MMC Test Rotors

PNNL will take the MMC plate and machine 4 rotors of each composition. The cast rotors will be machined to subscale rotor configuration and tested on an instrumented brake dynamometer at PNNL for friction characteristics (friction coefficient and wear rate) using several different pad compositions.

Task 4 - Material Characterization

Optical microscopy will be used to characterize the materials for composition, particle homogeneity and porosity levels

Complete

Task 5 - Brake Wear Testing

PNNL, utilizing the dynamometer, will run industry standard wear tests on the four produced MMC rotors. Post test characterization will be done to determine wear rate, friction coefficient with temperature, and analyze wear track and transfer layer chemistry.

Approach

Task Number & Brief Description	FY17				FY18				FY19				FY20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Raw Material Production **(Arconic Task)**																
Task 2: Casting of MMC Billet																
Task 3: Machining of MMC Test Rotors																
Task 4: Material Characterization **(Arconic Task)**																
Task 5: Brake Wear Testing																
Task 6: Final Report																

Milestone 1: Casting trials completed with rotor castings of each TiB2 loading level ready for machining into rotor test disks - 2nd Qtr FY18 – **Completed**

Milestone 2: Complete wear testing of at least one pad material paired with each of the TiB2 loading levels – 3rd Qtr FY20 – **In Progress**

Deliverable:

Final Report describing project results including wear and friction performance and material characterization.

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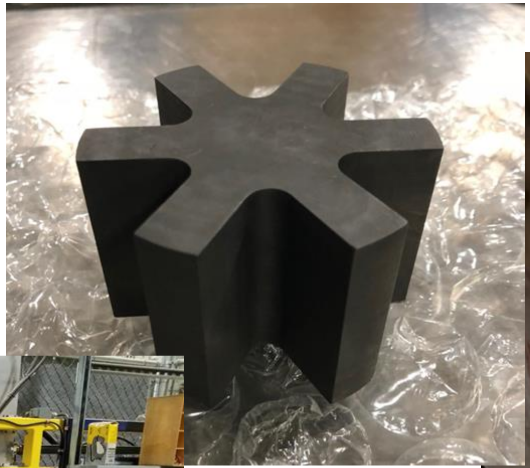
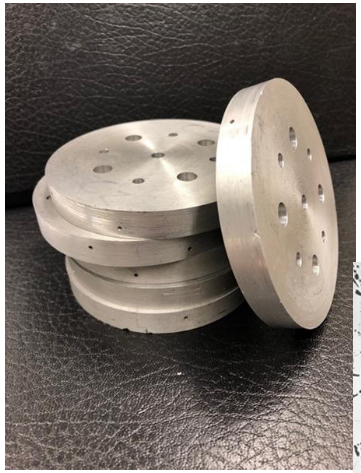
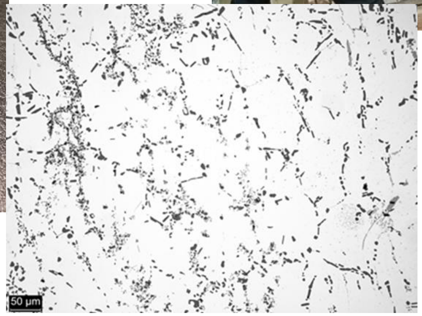
Accomplishments from Previous FYs

- Task 1 Raw Material Production (pressure infiltrate master alloy)
- Task 2 - Casting of MMC Plate
    - Trials involve melting A356 with appropriate amounts of 60% reinforced TiB_2-Al master alloy in PNNL stir casting machine. Gravity cast MMC book mold plates of MMC composition (5, 10, 15 vol% TiB_2) 8” x 12” x 1” thick
- Task 3 - Machining MMC Test Rotors (100 mm dia. x 12.5 mm discs)
- Task 4 - Material Characterization



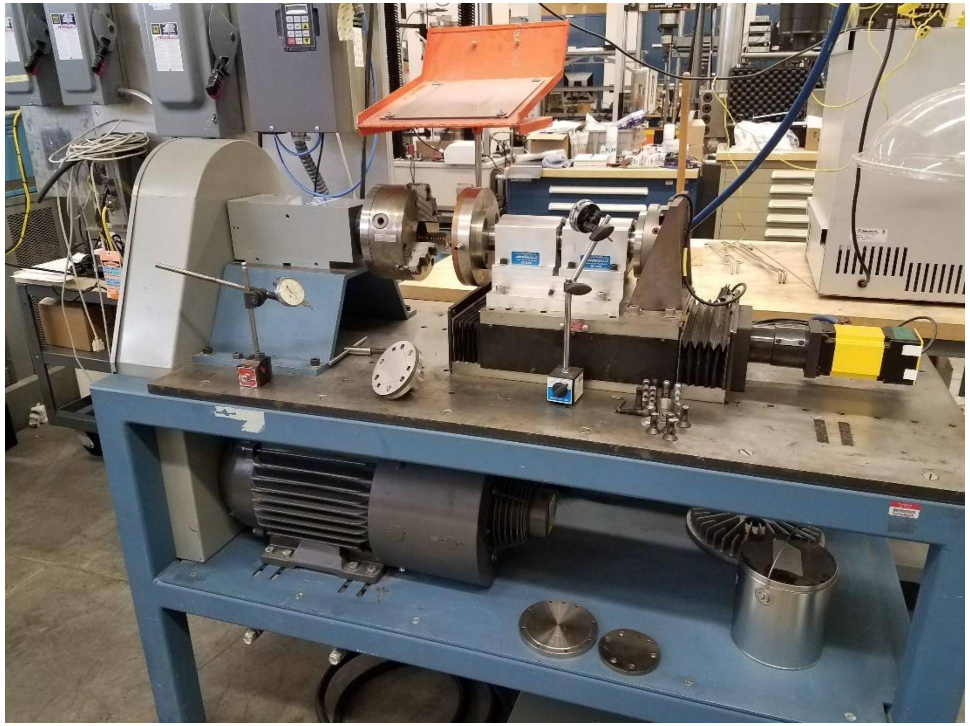




Accomplishments - Brake test stand Improvements

The focus during late FY19 and early FY20 was on further developing the test stand and materials for trials

- Friction pair test stand has been significantly upgraded with a better control system allowing us to vary more conditions during a test.
- Can now reach most of the conditions outlined in SAE J2522
- Improved motor drives, added more safety components and guards



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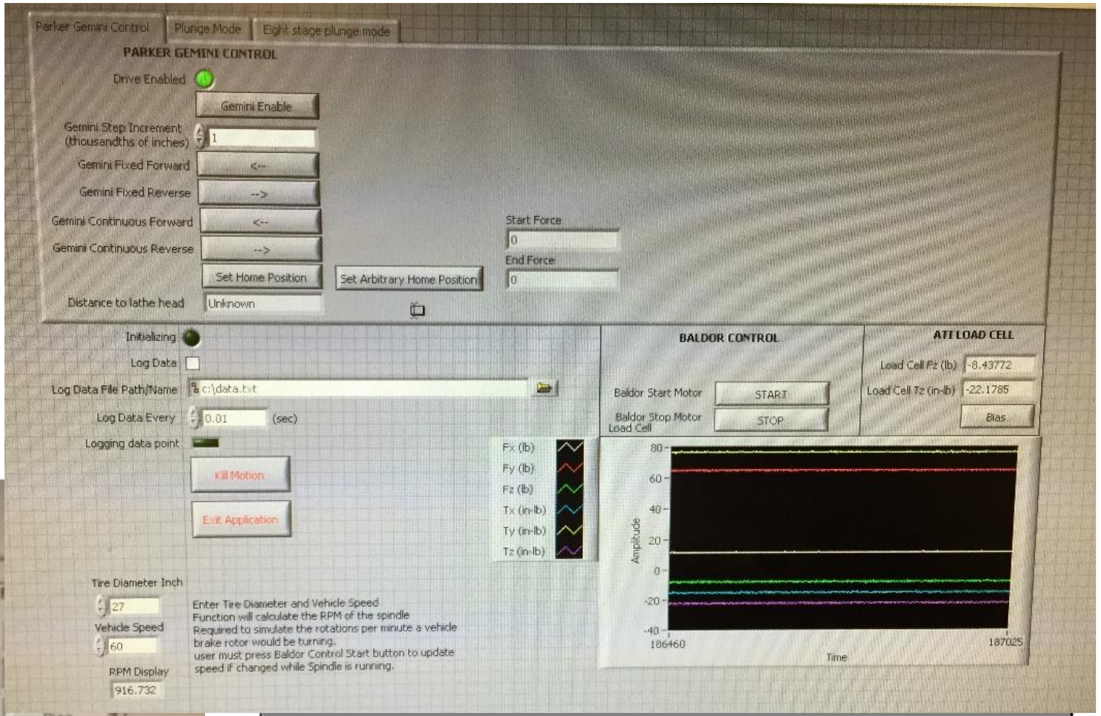
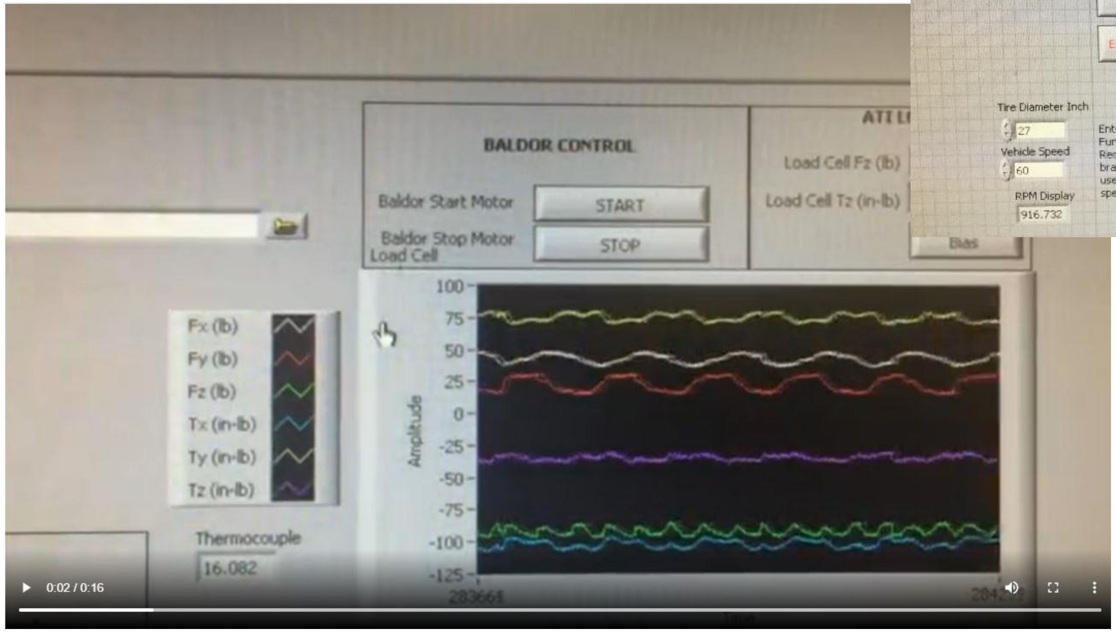
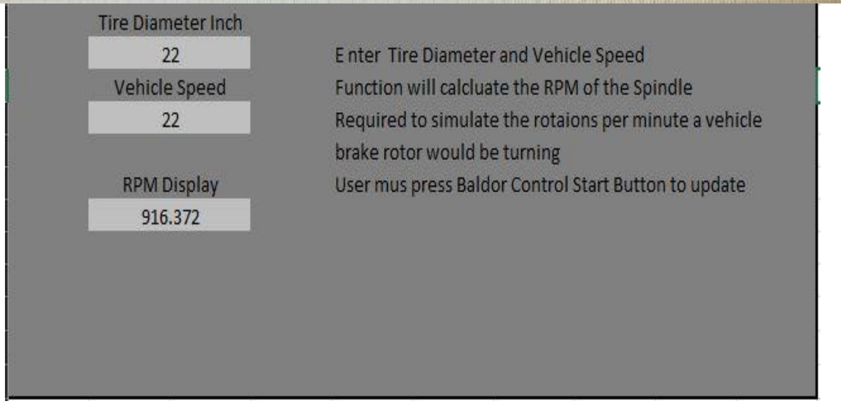
Accomplishments - Brake tester controls development

- User interface allows for :
  - Data capture sample rate changes
  - Real time trend of 6 Axis load cell
  - Adjustment of rotational axis speeds based on tire diameter and vehicle speeds
  - Temperature of rotor fixture capture allowing for control
  - Full control of x axis forces during testing
  - Biasing of load cell.



Can now control to most of the conditions outlined in SAE J2522



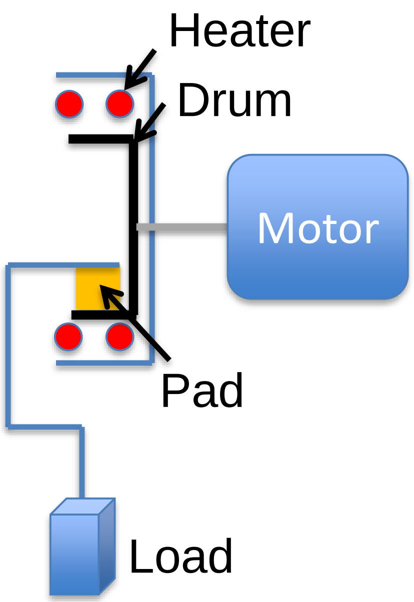


Accomplishments – Developing a test method

Comparison of Brake Tests and Standards

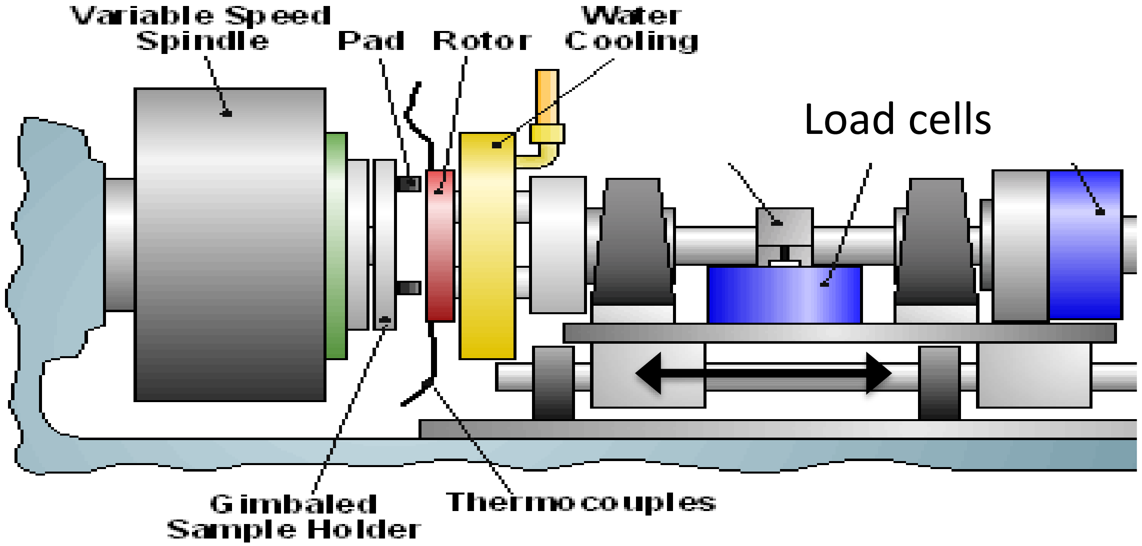
Chase

- Ideal for drum brakes
- Complete brake performance
- SAE J661



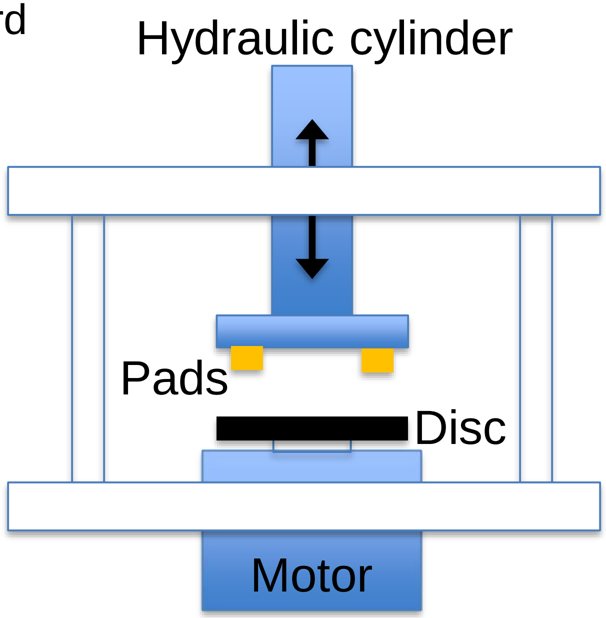
PNNL's Dynamometer

- Ideal for disc brakes
- Complete brake performance
- Widely-employed in industry
- Popular in literature
- Similar to SAE J2522



Krause or Pin-on-Disc Tests

- Very popular in literature
- Easy to find benchmark values or comparables, especially for the MMCs
- Ideal for wear rates
- Not standard



- In standard dynamometer pad is stationary in an actual caliper
- There is a flywheel between the motor and disc, Motor is disengaged during the test and rotor rotates free with the inertia of flywheel

Accomplishments – Developing a test method

Typical Data from Dynamometer and SAE J2522 used to define our test plan

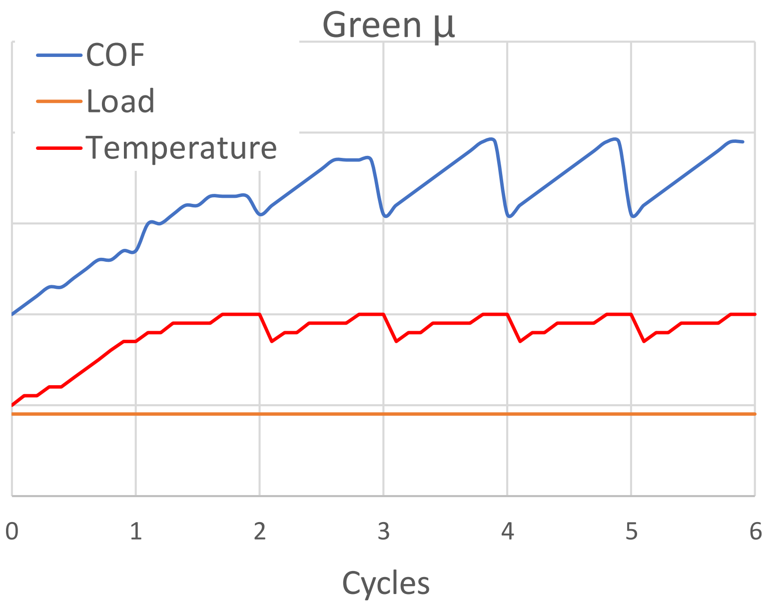
Green μ
- First contact
- Constant load
- μ increases and becomes stable
- T becomes stable

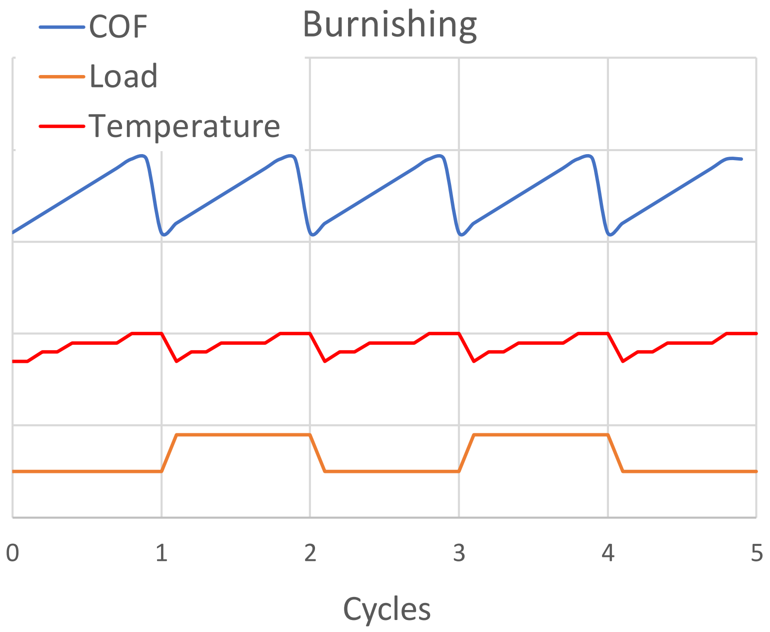
Burnishing
- Establishing a transfer layer
- Snub braking at varying loads

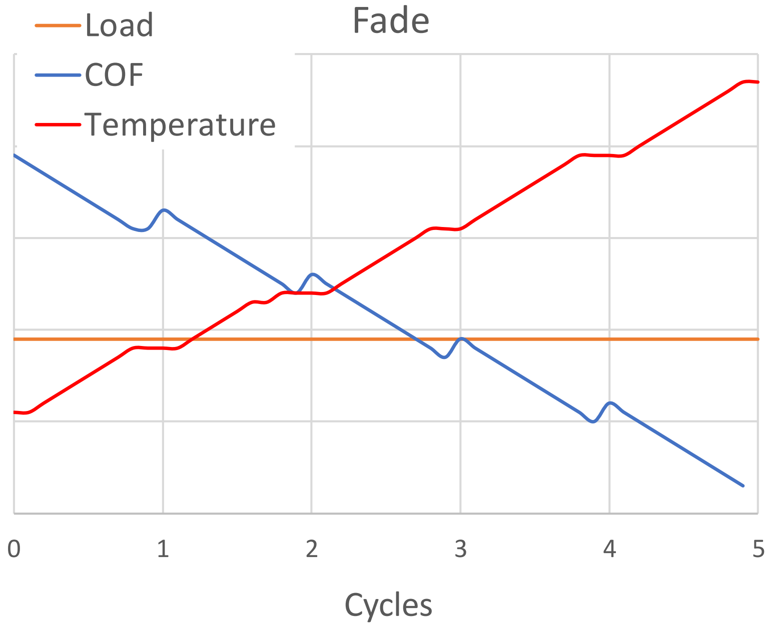
Sensitivity
- Various speed and loads
- μ as a function of speed and pressure

Fade
- Full stops
- Constant high load
- Temperature increases
- μ decreases

Recovery
- Snub braking
- Constant low load
- Low stable temperature
- μ increases and becomes stable



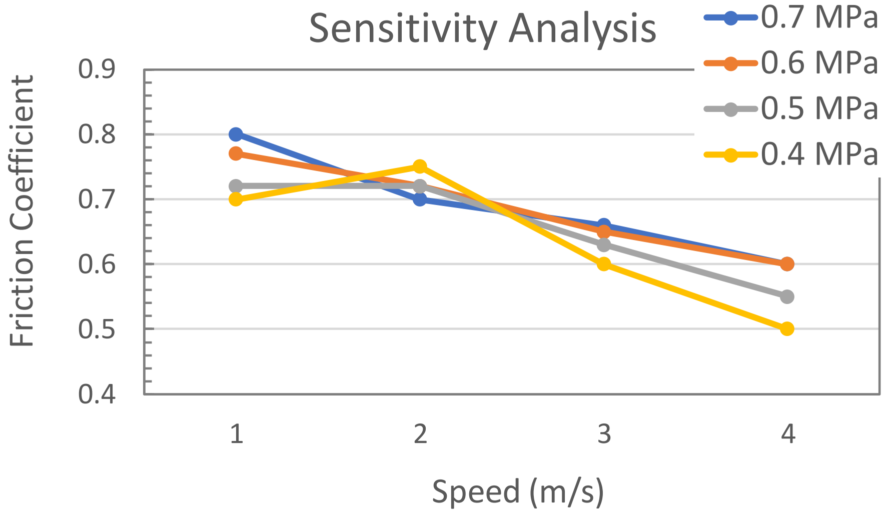


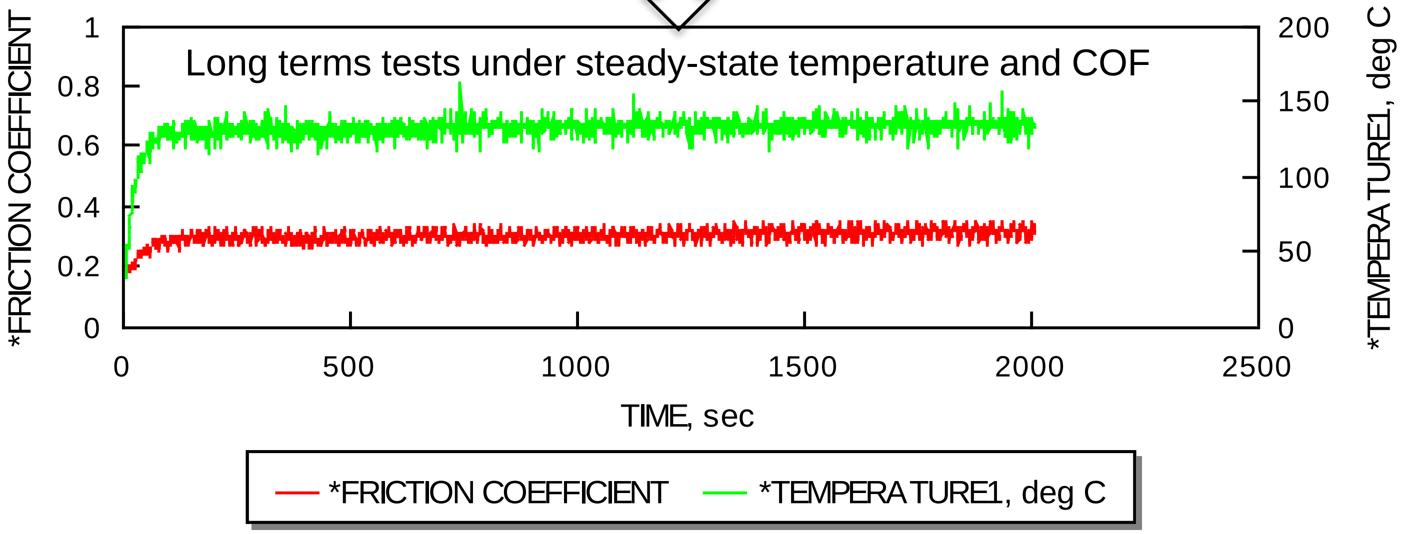


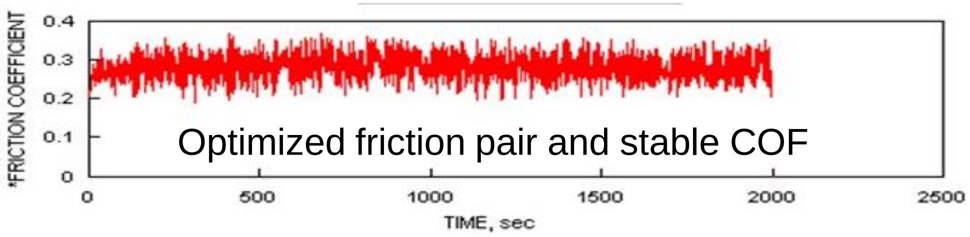
Accomplishments

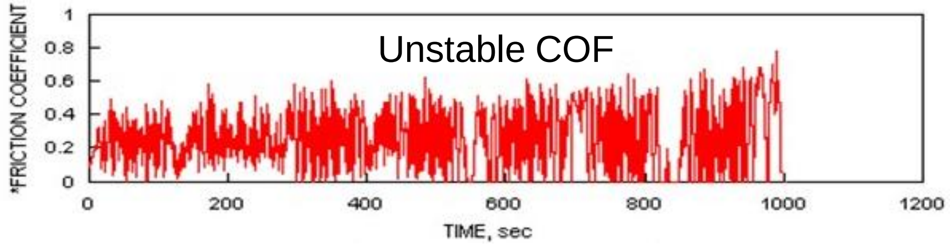
Test Plan Generated

- **First contact (green μ test) :** Increase initial brake temperature, stabilize μ
- **Burnishing:** Initial brake temperature (IBT) = 100 °C, speed = 4 m/s, varying pressure, 5 cycles
- **Constant interval test (Fade test)**: IBT = 25 °C, speed = 4 m/s, pressure = 0.9 MPa, 10 s drag – 10 s interval, 10 cycles
- **Speed and pressure sensitivity:** IBT = 25 °C, speed = 1, 2, 3, 4 m/s, pressure = 0.4, 0.5, 0.6, 0.7 MPa, 15 s (drag mode)
- **Wear test:** Constant temperature at two temperatures (150C and 400C), constant torque, speed = 4 m/s, pressure = 0.8 MPa, 1500 to 2000 secs

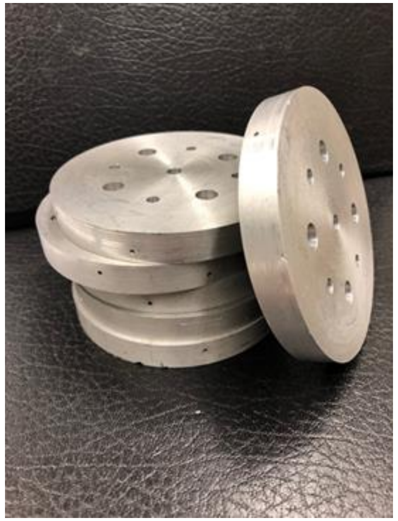


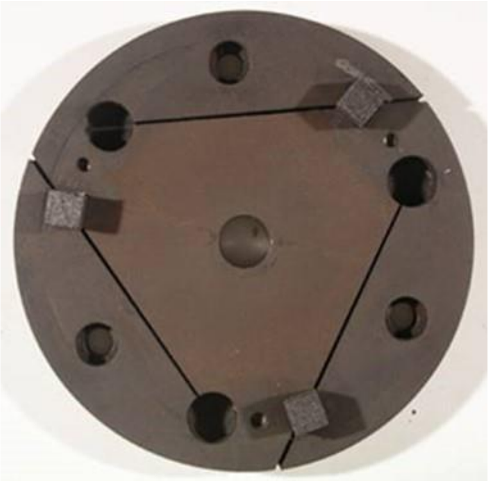






Accomplishments - Materials prepared for test trials





- Rotors have been fabricated in three TiB2 loadings: 5vol%,10vol% and 15vol%
- Five pads compositions have been selected based on the needs to benchmark against the earlier studies and based on an inferred difference in performance when coupled with an Aluminum MMC rotor
  - BBA2007 – the pad developed for the rear Al-MMC brake rotor on the Prowler
  - Porsche 911 GT3 Pagid - developed for the PCCB (C/SiC ceramic) brake rotor
  - EBC AF88-1 – an aggressive pad designed for cast iron rotors
  - AM R705 – a phenolic based pad designed for heavy vehicle disk brakes
  - Performance Friction Carbon Metallic – an aggressive pad designed for cast iron

Responses to Previous Year Reviewer Comments

- Reviewer 1: A reviewer commented about the complexity associated with various particle characteristics that can affect composite performance. The reviewer suggested an in depth sensitivity assessment, including more testing under various extreme conditions.
- *Answer 1: The project is scoped to evaluate the wetting and mixing of TiB2 into aluminum, test tribological properties of the resulting composite, and compare the results to a body of work on the tribology of Al-Sic composites. A more in depth study is a great suggestion, and with successful tribology test results, will be an appropriate follow-on scope as funding allows and industry support warrants.*

- Reviewer 2: Suggests that the project should examine the A356 silicon carbide centrifugal cast brake to benchmark the result of (TiB2) friction testing with the conventional rotor discs.
- *Answer 2: Centrifugal cast A359/SiC rotors were investigated by PNNL in earlier DOE VT studies and found to have very good performance. Past project results on centrifugal cast rotors, as well as on conventionally cast 359/SiC, and on baseline cast iron rotors will be compared against A356/TiB2 wear rate results from this study.*

Collaboration and Coordination with Other Institutions

Arconic Tasks

Resources: Ceramic TiB_2 fabrication, Multi-scale, multi-method casting equipment, microstructural characterization

- **Task 1 - Raw Material Production**
  - Arconic Technology Center (ATC) will produce 70kg-50 volume percent Al-TiB2 master alloy. ATC will provide a 150kg A356 casting alloy to PNNL.
- **Task 4 - Material Characterization**
  - ATC will characterize the materials for composition and mechanical properties

PNNL Tasks

LightMat Resources: MC21 MMC Stir Casting Equipment, Brake rotor/pad friction pair wear testing / Brake dynamometer testing equipment

- **Task 2 - Casting of MMC Plate**
  - PNNL will utilize the MMC stir casting equipment to cast MMC plates (5, 10, 15 vol% TiB2)
- **Task 3 - Machining MMC Test Rotors**
  - PNNL will take the MMC plate and machine 4 rotors of each composition
- **Task 5 - Brake Wear Testing**
  - PNNL, utilizing the dynamometer, will run industry standard wear tests on the produced MMC rotors.

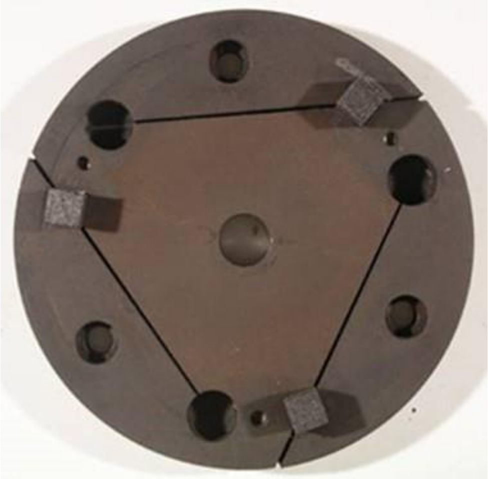
Proposed Future Research

Remaining Tasks Evaluation of Friction Pairs - Subscale testing

- Friction Pair Testing
  - 10 cm diameter rotor disks
  - Test run at constant torque for fixed time
  - Rotor temperatures measured by thermocouple 2-5 mm below friction surface
  - Temp maintained by cooled backing plate

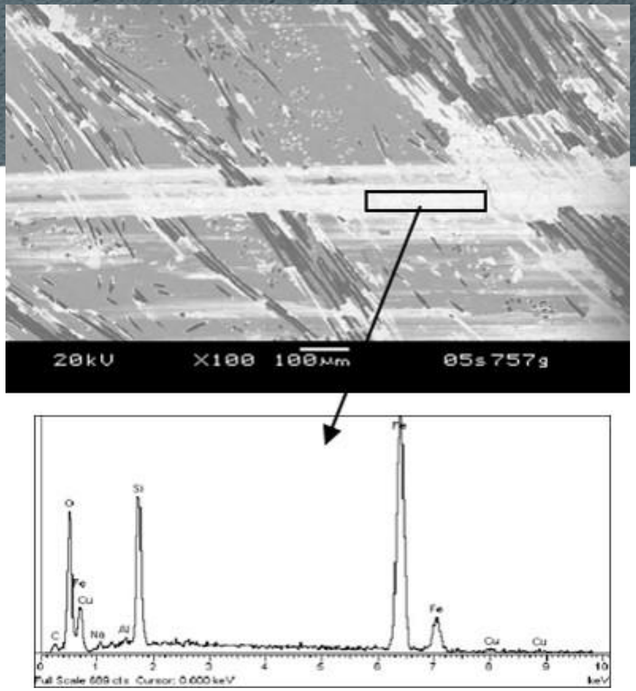
- Three 0.5 x 0.5 x 1 cm pads are mounted to gimbaled holder and rotated against the pads
- Axial loads required to maintain torque are measured
- Friction coefficients are then calculated and post test weights are used to calculate wear rate

Wear tester at PNNL



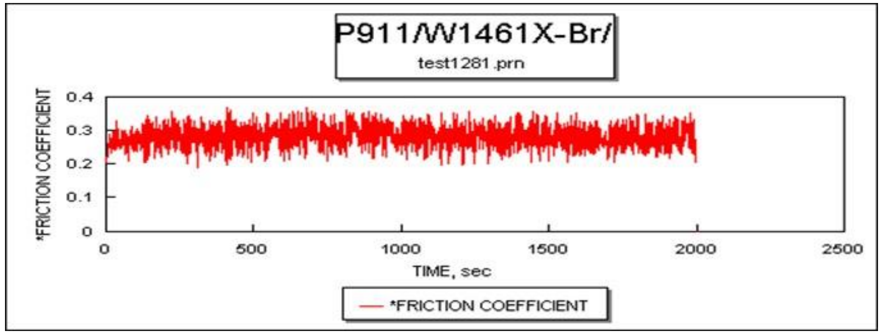
Any proposed future work is subject to change based on funding levels

Proposed Future Research
Remaining Tasks Tribology Characterization

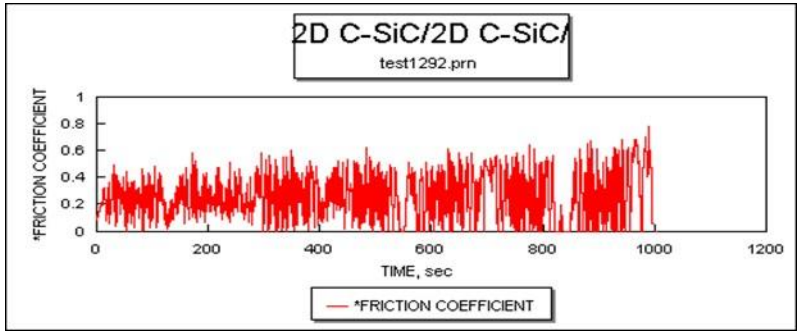


SEM EDX analysis of transfer layer

- Tribologic characterization helps to define appropriate friction pairs
- The development of a stable transfer layer is key to stable friction coefficients



When appropriate friction pairs are used, stable friction coefficients result

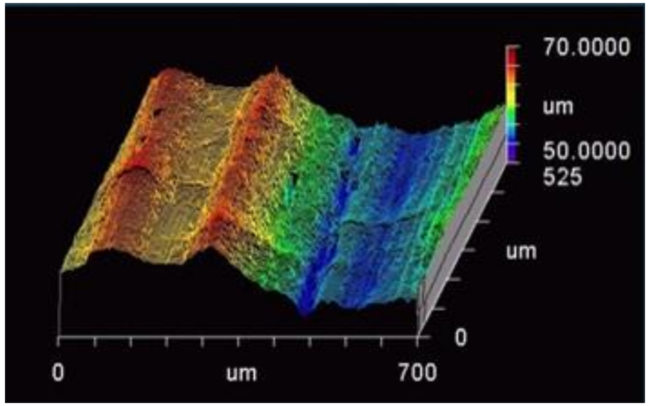


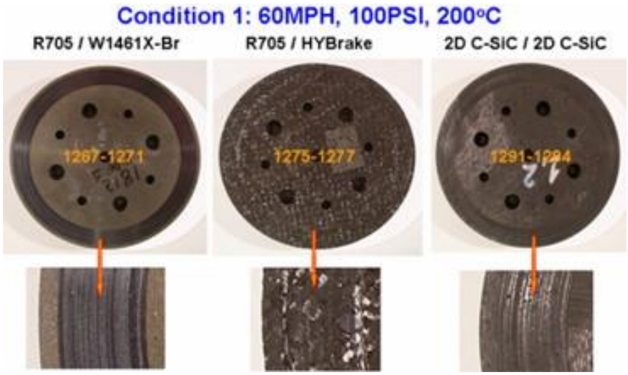
When the pair is not optimized the system is unstable

Proposed Future Research

Remaining Tasks — Measurement of specific wear rate

- Specific wear rate (mm^3/Nm) = $\dfrac{V}{F_N d}$
- V: wear volume, F_N : normal force, d: sliding distance
- V can be found from:
  - V of the rotor materials will be measured by the average depth of the wear track from 36 scans (every 10^o) around the wear track using a laser profilometer.
  - V for the pads is a measurement of the pad thickness with a micrometer at the end of each test.
  - The rotor wear rates will be normalized using the ratio of the swept area on the rotor vs. the area of the three pads.





Typical wear tracks for cermets and C/SiC rotor materials

Any proposed future work is subject to change based on funding levels

Summary

Why a LightMat Project?

- Technology / Commercial opportunities have changed in the last decade offering an opportunity to re-evaluate Al-MMC brake rotors.
- The Pacific Northwest National Lab has test equipment, expertise and a large historical database on SiC (and other) based MMC brake performance from previous projects, which can be compared to Arconic's new TiB_2 reinforcement concepts.
- Baseline performance data developed in this project will allow Arconic to evaluate the viability of a new Al-MMC concept, and move towards commercialization in a lower risk environment.

Approach

- This project will investigate using Titanium Diboride (TiB_2) as a substitute for the more traditional MMC efforts with Silicon Carbide (SiC) in an effort to improve automotive brake performance, wear life, and reduce cost.

Impact

- A 50% weight saving in the rotor has been calculated to correspond to an improvement in fuel economy of 0.25 mpg due to weight reduction and lower rotational inertial energy losses
- Al MMC rotors, using TiB_2 have the potential to show lower overall fabrication and life cycle cost and better performance in wear and wear particulate emission over current cast iron.

Technical Backup Slides

Previous work - Dyno Testing Results of Alum SiC MMC rotors

Test Description		Testing Source	Pass (P), Nonconforming (N)	Remarks / Reaction Plan for Nonconforming Items
Dyno Simulation of AMS &Fade test.		Link Engineering	Pass(P)	AMS results are promising .
Dyno Simulation Of Laurel Mountain Hot Roughness Brake test-		Link Engineering	Pass(P)	Rotor passes the test. Need to increase Brake Caliper roll back space to compensate thermal expansion of Rotor prevent scoring.
Dyno lining Wear Vs Temperature		Link Engineering	Pass(P)	Need to develop new lining for ALMMC, this Akebono lining is decomposing faster at 300C or higher temperatures.
Env. Dyno Brake Noise Test (w/steady drag)		Link Engineering	Pass (P),	Need to develop new lining for ALMMC, this Akebono lining is at the border line of Noise Index, rating is Yellow.
Disc Wear w/Low Pressure Drag		Link Engineering	Pass (P)	Disc wear loss for MC21 is negligible. Recommendation is use only MC21 or 20% or higher SiC.
Dyno Brake Effective Test		Link Engineering	Pass(P)	Results are promising, however in temperature sensitivity cycle temperature reaches to above 500 deg Celsius because Link did not stop the test at 400 deg C. parts survived 500 deg C test.